Stabilization of tokamak plasma by lithium streams

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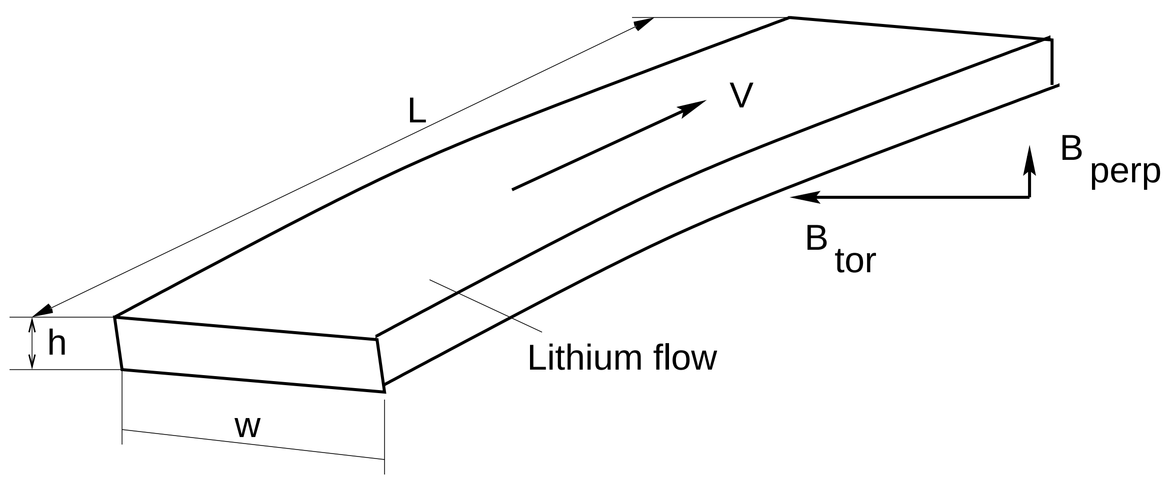
OUTLINE

1. Basics of liquid lithium MHD.
2. Flow pattern of magnetic propulsion.
3. Theory of stabilization.
4. Flow locked mode.
5. Compatibility with fusion reactor.
6. Prospects for high beta.

1 Basics of liquid lithium MHD

There 3 magnetic Reynolds numbers which control lithium MHD in tokamaks

$$\begin{aligned} \text{dynamics}: &\quad \Re_0 \equiv \mu_0 \sigma L V, \\ \text{electro-dynamics}: &\quad \Re_1 \equiv \mu_0 \sigma h V, \\ \text{dynamics}: &\quad \Re_2 \equiv \mu_0 \sigma \frac{h^2}{L} V, \\ &\quad \mu_0 \sigma \simeq 4 \ \left[\frac{sec}{m^2}\right]. \end{aligned} \tag{1.1}$$



Characteristic flow parameters:

$$
\begin{aligned}
V = 20\ m/sec &\rightarrow \rho\frac{V^2}{2} \simeq 1\ [atm], \\
B = 1\ T &\rightarrow \frac{B^2}{2\mu_0} = 4\ [atm], \\
B = 5\ T &\rightarrow \frac{B^2}{2\mu_0} = 100\ [atm].
\end{aligned}
\tag{1.2}
$$

Dynamic pressure losses are determined by $\Re_0$ and $\Re_2$

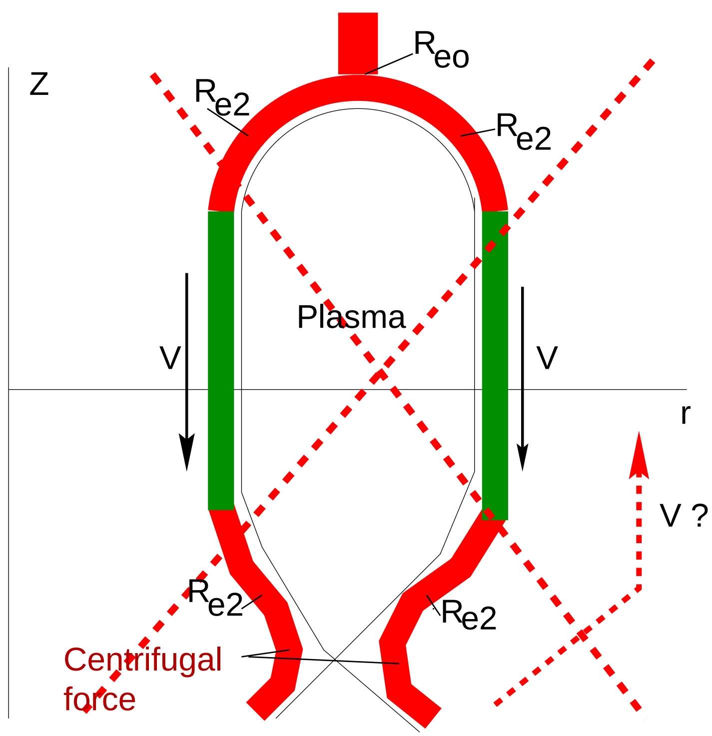
$$
\begin{aligned}
\Re_0: &\quad \Delta\rho\frac{V^2}{2} = \mu_0\sigma L V\frac{B_\perp^2}{2\mu_0}, \\
\Re_2: &\quad \Delta\rho\frac{V^2}{2} = \mu_0\sigma\frac{h^2}{L}V\Delta\frac{B_\parallel^2}{2\mu_0}, \\
&\quad \mu_0\sigma \simeq 4\ \left[\frac{sec}{m^2}\right].
\end{aligned}
\tag{1.3}
$$

Magnetic fields from the currents in the stream are determined by $\Re_1$

$$
\Re_1: \quad B_{||out} - B_{||in} = \mu_0\sigma h V B_\perp. \tag{1.4}
$$

Lithium “water-falls” are incompatible at the basic level with the tokamak strong toroidal field

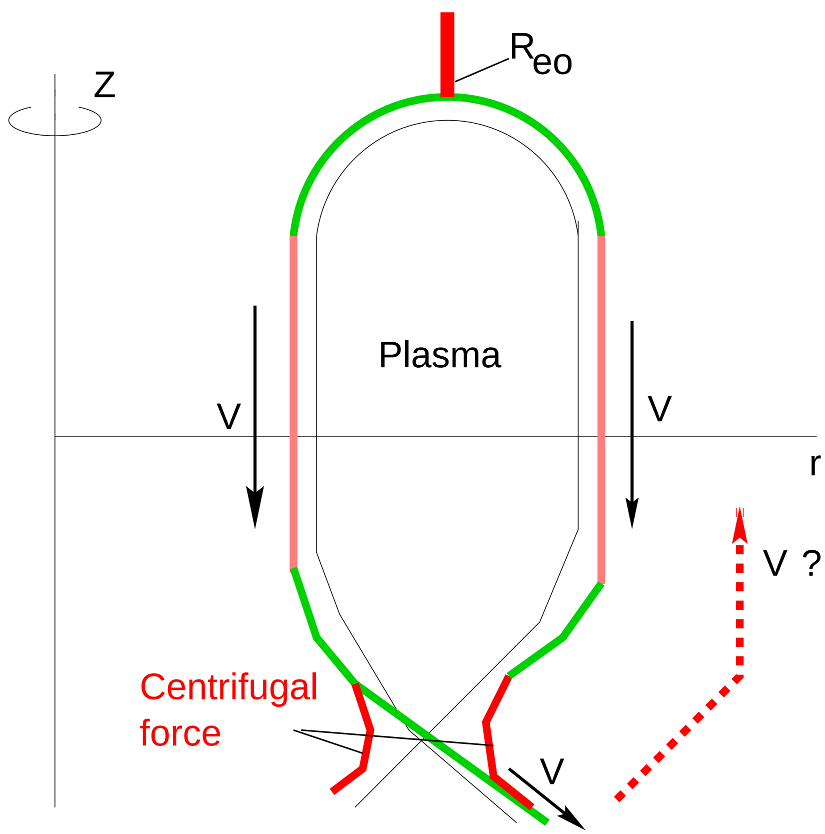
$$\begin{aligned} &h = 0.1\ m, \quad L_1 \simeq 0.2\ m, \quad L_2 \simeq 3\ m, \quad V > 2-5\ [m/sec], \\ &\Re_0 = 4L_1V => 1.6, \\ &\Re_2 = 4\frac{h^2}{L_2}V = 4\frac{h}{L_2}(hV) \simeq 0.01 - 0.025. \end{aligned} \qquad (1.5)$$



$$\boxed{\rho\frac{V^2}{2} \ll \Re_2 \Delta \frac{B_{tor}^2}{2\mu_0}}$$

Momentum driven thin walls have a lot of unresolved problems in lithium MHD

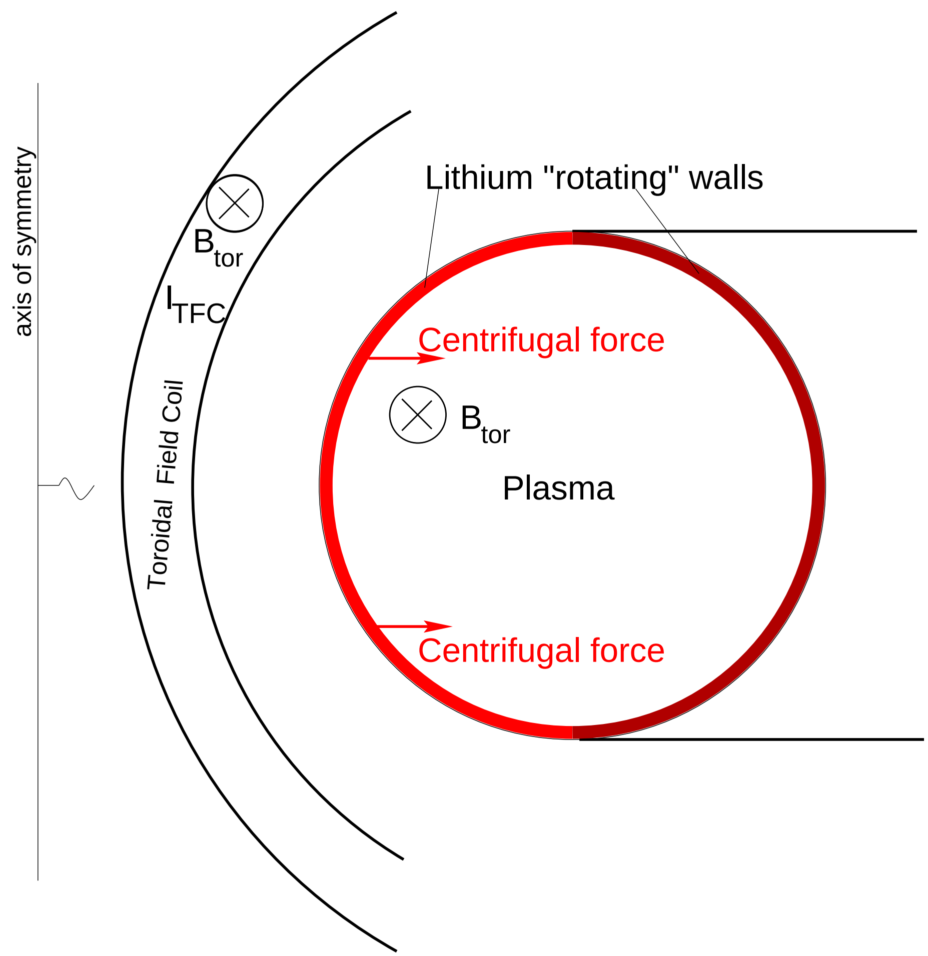
$$h = 0.01\ m, \quad L_1 \simeq 0.02\ m, \quad L_2 \simeq 3\ m, \quad V \simeq 20\ [m/sec],$$
$$\Re_2 = 4\frac{h^2}{L_2}V \simeq 1.3 \cdot 10^{-4}. \tag{1.6}$$



$$\boxed{\Re_0 = 1.6, \quad \rho\frac{V^2}{2} < \Re_0\frac{B_{pol}^2}{2\mu_0}}$$

2 Flow pattern of magnetic propulsion

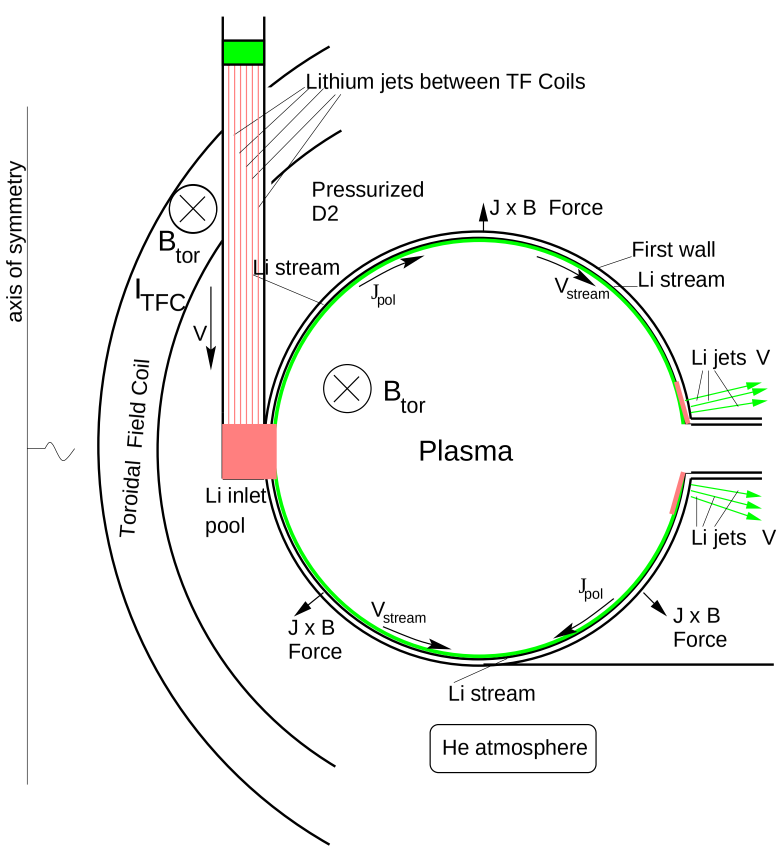
"Rotating" liquid lithium walls are incompatible with tokamaks.



- no inlet/outlet
- poloidal rotation damps as $R\rho\frac{dV}{dt} \simeq \Re_2 \frac{B_{tor}^2}{2\mu_0}$
- toroidal rotation is impossible due to centrifugal force.

Magnetic propulsion makes MHD of intense lithium streams compatible with tokamaks (at least at the basic level).

$$p_{\mathbf{j}\times\mathbf{B}}\big|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}\big|_{outlet} \gg \Re_2 \frac{B_{tor}^2}{2\mu_0}, \qquad \Re_2 \equiv \mu_0\sigma\frac{h^2}{R}V \simeq 0.0015$$



- Driving electromagnetic pressure $p_{\mathbf{j}\times\mathbf{B}}\big|_{outlet} > 1\ atm$

  $$p_{\mathbf{j}\times\mathbf{B}}\big|_{inlet} - p_{\mathbf{j}\times\mathbf{B}}\big|_{outlet} \simeq 1.5-3\ [atm]$$

- Flow parameters

  $$V \simeq 20\ m/sec, \qquad h \simeq 0.01\ m$$

- Magnetic Reynolds numbers

  $$\Re_1 \equiv \mu_0\sigma hV \simeq 0.8, \qquad \Re_2 \simeq 0.0015$$

- Stream are robustly stable due to centrifugal force

  $$\rho\frac{\langle V^2\rangle}{2} > \frac{a}{2R}p_{wall}n_r$$

3 Theory of stabilization

Flow pattern of magnetic propulsion eliminates the possibility of mode locking into the conducting wall (“Rotating” walls do nothing).

The theory includes an arbitrary geometry of the guide wall

$$\mu_0\tilde{\mathbf{j}}_w \equiv \frac{\nabla\rho\times\nabla I}{\delta a} = -\frac{I'_\varphi}{J_w}\mathbf{e}_\theta + \frac{I'_\theta}{J_w}\mathbf{e}_\varphi, \qquad J_w \equiv r_w(\theta)h(\theta)\sqrt{g_{\theta\theta}}, \quad g_{\theta\theta} = (r_w)'^2_\theta + (z_w)'^2_\theta. \tag{3.1}$$

It links the electric current in the streams with parameters which can be extracted from existing numerical codes

$$(\mathsf{D}_v - \mathsf{D}_p)\vec{\psi}(a) = -i\mathsf{M}\vec{I}. \tag{3.2}$$

For arbitrary tokamak configuration, arbitrary cross-section and flow pattern, it formulates the equation for electric current in the streams and leads to a dispersion relation for the growth rate

$$(\mathsf{D}_v - \mathsf{D}_p)\vec{\psi} = \mu_0 h\sigma\gamma(\mathsf{MS}^{-1}\mathsf{M})\vec{\psi} + i\Re_1(\mathsf{MS}^{-1}\mathsf{VM})\vec{\psi}. \tag{3.3}$$

(see, PPPL report at http://www.pppl.gov $\Longrightarrow$ Meetings $\Longrightarrow$ Lithium Walls 2000)

Dispersion relation for the cylindrical case

$$a\Delta'_m\psi_m = \tau_{res}\gamma\psi_m + \Re_1\sum_k (m+2k+1)v^*_{2k+1}\psi_{m+2k+1}, \tag{3.4}$$

where

$$\tau_{res} = \mu_0\sigma h a, \qquad v_{2k+1} = \frac{2}{i\pi(2k+1)}, \qquad v_{2k} = 0. \tag{3.5}$$

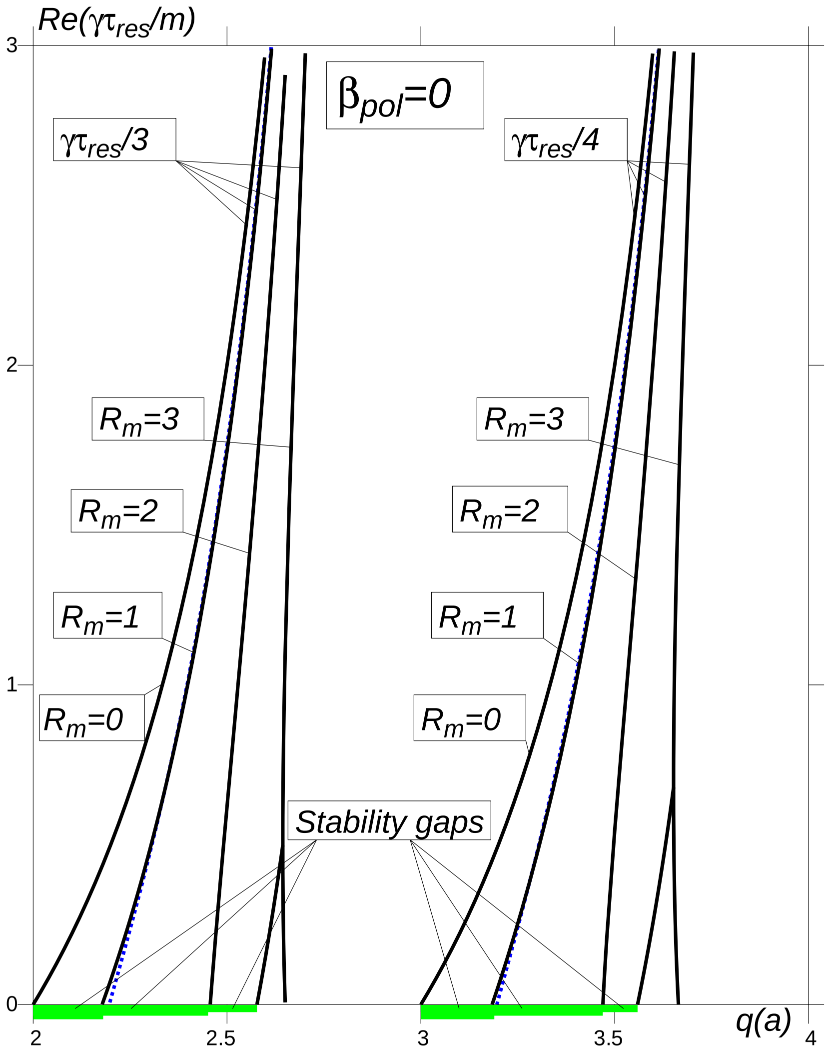
There is coupling with a nearest satelite modes and then, with each second satelite mode.

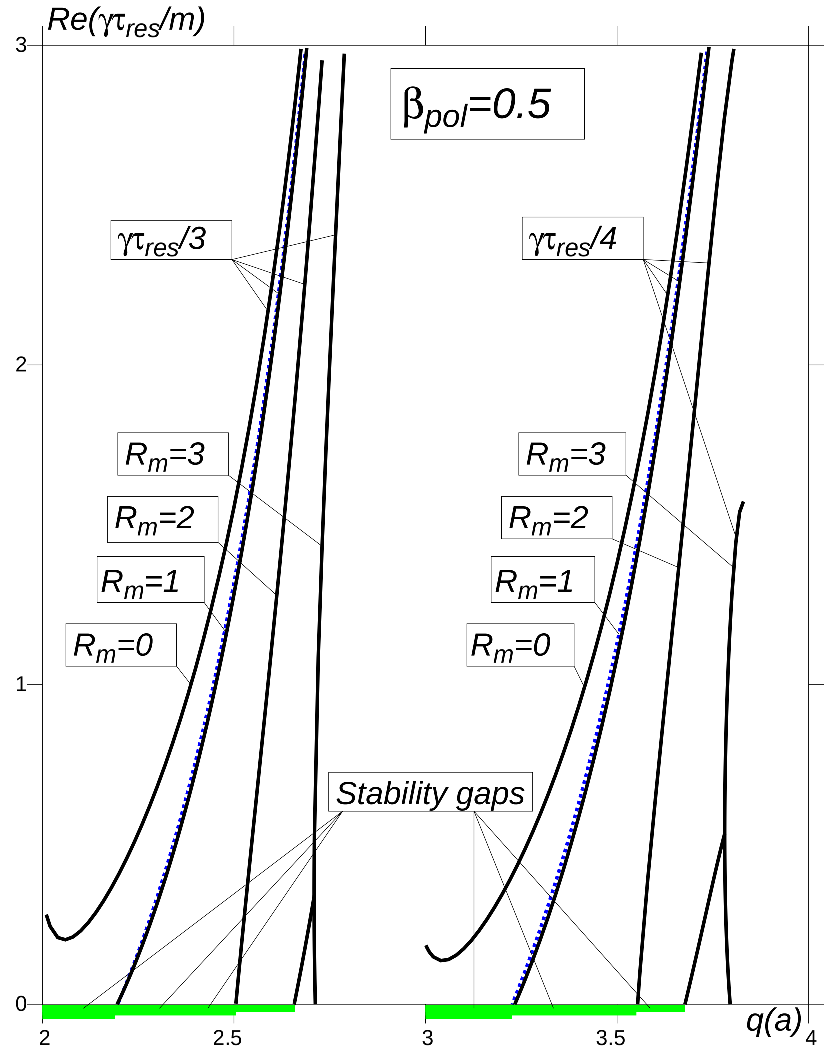
Three harmonics approximation immediately shows the stabilizing effect

$$\begin{aligned} &a\Delta'_m - \tau_{res}\gamma \\ &+ \frac{m(m+1)\Re_1^2|v_1|^2}{a\Delta'_{m+1} - \tau_{res}\gamma} + \frac{m(m-1)\Re_1^2|v_1|^2}{a\Delta'_{m-1} - \tau_{res}\gamma} = 0. \end{aligned} \tag{3.6}$$

It also shows possibility for the mode, which is locked into one of streams.

Stability gaps are insensitive to m-number. Finite β can be stabilized.

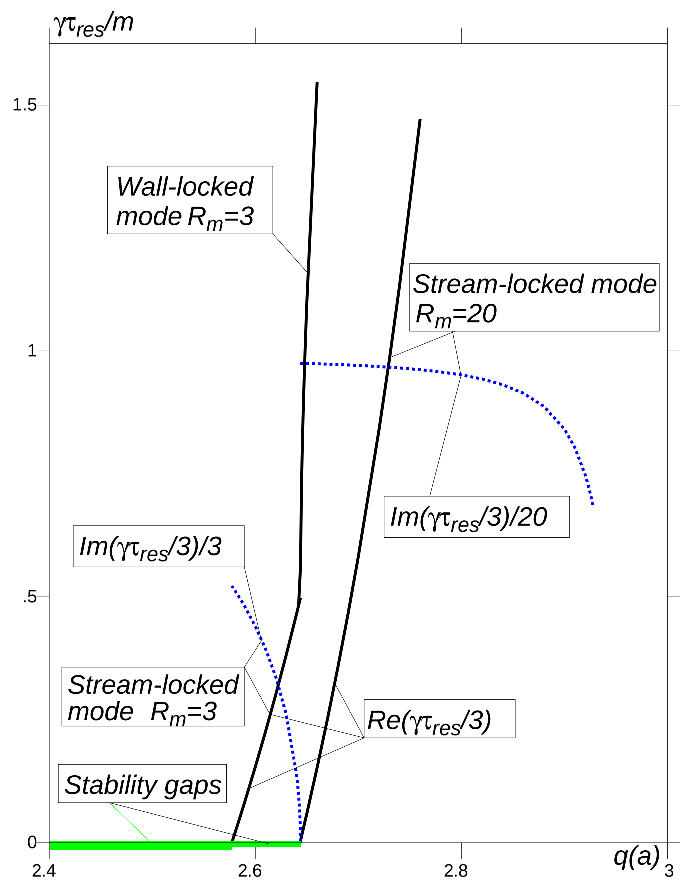


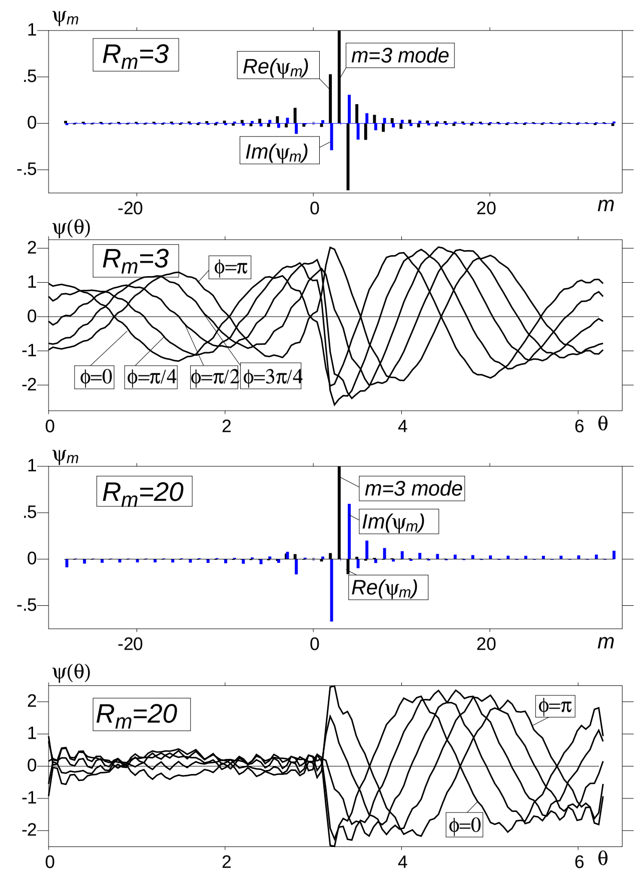


4 Flow locked mode

Resistive wall mode is well affected by the flow.

Flow-locked mode determines limits of stabilization.





5 Compatibility with fusion reactor

Can use of lithium provide a new path for fusion ?

Integrated approach to fusion reactor

Plasma science part

Solid Li

New plasma regime:

suppressed turbulence,
second stability,
resistive wall at the
plasma boundary, ...

Liquid Li

Technology opportunities:

for Plasma Facing Comp.,
power extraction,
liquid (FLiBe) blankets, ...

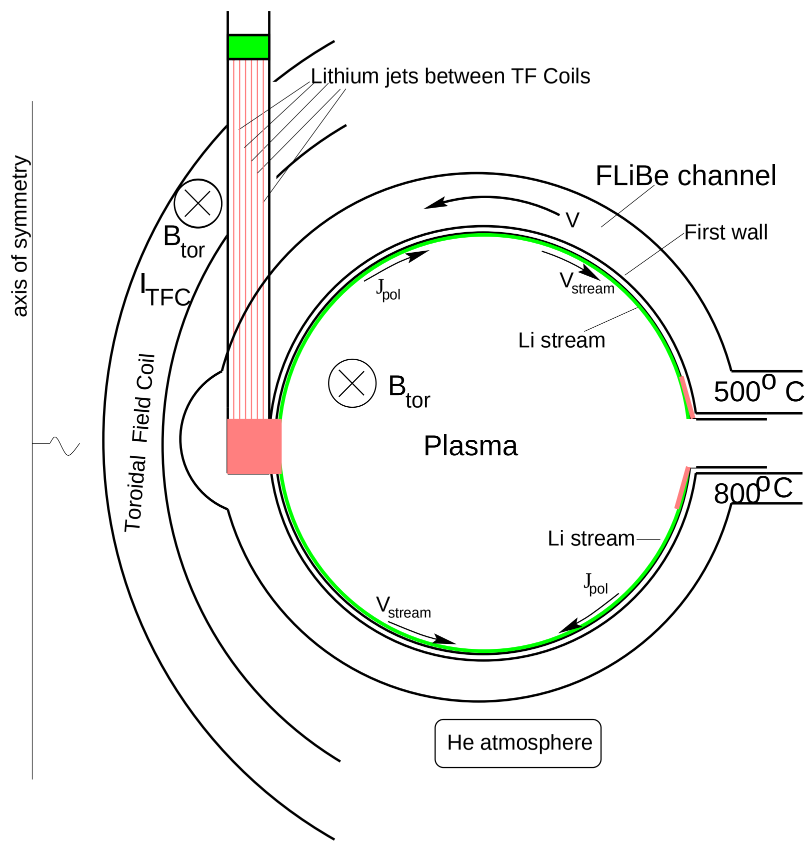
New schemes for the tokamak reactor:

reduced activation,
smaller size and Btor,
reduced reliance on shaping and
high-tech plasma control
...

Opportunity for studies of new plasma regimes and developing liquid lithium technology in a separate (parallel) manner.

6 Compatibility with fusion reactor

Intense lithium streams + FLiBe make an excellent FW/blanket combination (S.Zinkle, B.Nelson, ORNL)



Lithium streams keep the wall temperature below melting point of FLiBe

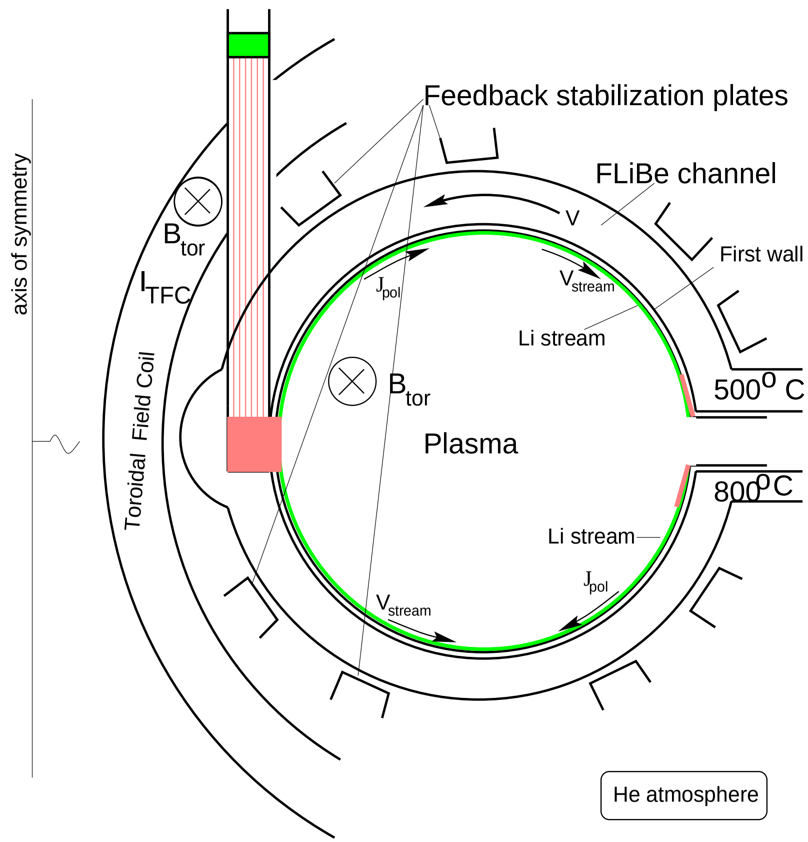
$$\boxed{T_{wall} \simeq 200^o - 250^0 < T_{melt,FLiBe} \simeq 450^o}$$

Independent of inner temperature in the chanell FLiBe has a solid boundary layer at the walls.

Even with $\boxed{T_{FLiBe}|_{outlet} = 800^o\ C}$ energy losses on the side walls are $\simeq 4\%$.

How crazy if would be to think about making the vacuum chamber from the wire mesh

It also creates the best possible situation for plasma stability control:

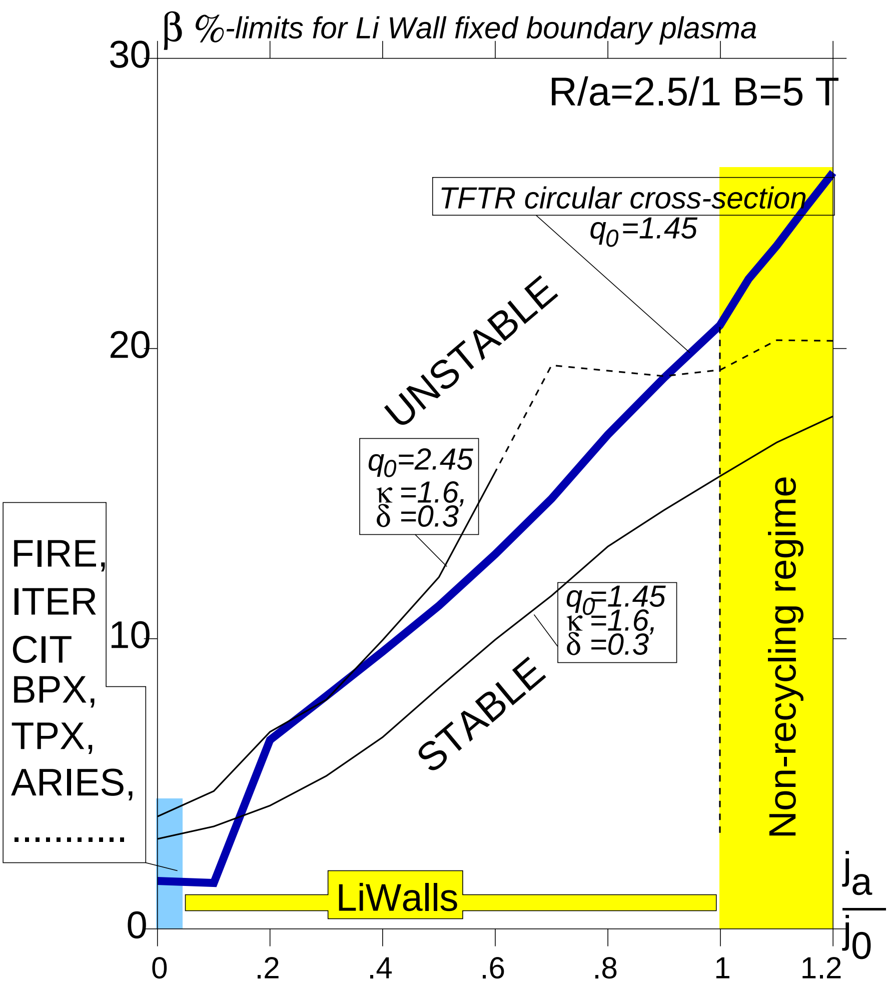


- “passive” conducting shell at the plasma boundary;
- protection of feedback stabilization plates from 14 MeV neutrons;
- accessibility to feedback stabilization plates;
- no-conducting structures between feedback plates and conducting shell;
- additional stabilization by the lithium streams (for free);

At present, there is no credible schemes for MHD plasma control in neutron environment in any of existing so-called “reactor” concepts.

7 Prospects for high beta

With fix boundary plasma & flatenned temperature profile this concept would result in a new core MHD regime:



- no sawtooth oscillations;
- no Troyon limit;
- free access to the second stability zone;

β - limits for the second stability regime

- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON)
- current density with an edge pedestal

$$\mathbf{j}_{\parallel} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$